Journal of Power Sources 257 (2014) 335–343

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Design and control strategy for a hybrid green energy system for mobile telecommunication sites

Michael S. Okundamiya [a,*], Joy O. Emagbetere [b], Emmanuel A. Ogujor [b]

[a] Department of Electrical and Electronic Engineering, Ambrose Alli University, Ekpoma 310006, Nigeria
[b] Department of Electrical/Electronic Engineering, University of Benin, Benin City, Nigeria

HIGHLIGHTS

- This study develops the optimum control model for HGES.
- Applies genetic-algorithm for optimal techno-economic sizing of system's components.
- Determine viability of proposed HGES in terms of the system's energy throughput.
- Implementation of proposed HGES gives an average throughput of over 12 kWh US^{-1}.

ARTICLE INFO

Article history:
Received 20 November 2013
Received in revised form
3 January 2014
Accepted 31 January 2014
Available online 8 February 2014

Keywords:
Control strategy
Energy efficiency
Genetic algorithm
Green-energy system
Mobile telecommunication
Techno-economic sizing

ABSTRACT

The rising energy costs and carbon footprint of operating mobile telecommunication sites in the emerging world have increased research interests in green technology. The intermittent nature of most green energy sources creates the problem of designing the optimum configuration for a given location. This study presents the design analysis and control strategy for a cost effective and reliable operation of the hybrid green energy system (HGES) for GSM base transceiver station (BTS) sites in isolated regions. The design constrains the generation and distribution of power to reliably satisfy the energy demand while ensuring safe operation of the system. The overall process control applies the genetic algorithm-based technique for optimal techno-economic sizing of system's components. The process simulation utilized meteorological data for 3 locations (Abuja, Benin City and Sokoto) with varying climatic conditions in Nigeria. Simulation results presented for green GSM BTS sites are discussed and compared with existing approaches.

1. Introduction

The use of fossil-fueled generators for powering GSM BTS sites presents a number of environmental, economic, and logistical challenges [1–3]. The growing need for energy sustainability has made the alternative energy sources a promising research area. The world trend in recent times is to find a clean and non-depleting source of energy or the combination of various sources with minimal or no adverse effects on the environment. This has increased interest in energy saving and environmental protection, which could be achieved through the extensive utilization of green (renewable) energy sources/technologies [4–11]. Green energy technologies are essential components of sustainable development mainly because of the following reasons [7]. Firstly, they are more eco-friendly than other sources/technologies as such extensive utilization of the green option will help in making the environment more friendly and safe. Secondly, they are non-exhaustible and if properly utilized in appropriate application, they can provide a reliable and sustainable supply of energy almost indefinitely. Thirdly, they favor system decentralization and local solutions that are somewhat independent of the utility grid. This enhances the flexibility of providing enormous benefits to small isolated populations.

The hybrid green energy systems are capable of providing the needed energy for sustainable economic development in the mobile telecommunication sectors but critical issues on the enabling technologies are yet to be resolved. The dynamic interaction between the green energy sources and the energy demand can lead to system instability and this could reduce the

* Corresponding author. Tel.: +234 8066263858.
E-mail addresses: msokundamiya@aauekpoma.edu.ng, st_mico@yahoo.com (M.S. Okundamiya).

http://dx.doi.org/10.1016/j.jpowsour.2014.01.121
0378-7753/

reliability and quality of the power supplied. It is worthy of note that the operational specifications of green energy systems are location dependent [11]. Potential investors are at a cross road on the choice of system design configuration, optimum specifications, capacity projections and the techno-economic implications. Furthermore, key performance indicators that could influence investor's choice on the most suitable technology or its combinations are increasingly lacking in the literature. In addition, green energy solutions are not commonly used for powering GSM BTS sites in Nigeria presently [12]. Consequently, more research work on new alternative (hybrid) energy systems and the enabling technology for a sustainable economic development is needed.

This paper focuses on the design and control strategy for a reliable operation of the hybrid green energy system for GSM BTS sites. The main objective is to minimize the techno-economic cost of the hybrid green energy system for the global expansion of mobile services in isolated regions.

2. System design analysis/techno-economic sizing

The green-mobile solution refers to the use of efficient energy infrastructure and the application of green energy technologies for GSM BTS sites. Fig. 1 shows the proposed hybrid green energy system architecture. It consists of two green technologies; wind energy and photovoltaic (PV) conversion systems, with provision for future expansion, energy storage system and the control circuitry. The wind energy and PV conversion systems consist of one or more wind turbine generators (WTGs) and PV array respectively, while the control system is made up of the power electronics and system controller. The GSM BTS site consists of the BTS, which consists of the baseband, radio frequency and feeder, and other auxiliary equipment such as the cooling and lighting systems [13]. Some mobile vendors have designed BTS based on the actual local climate conditions. These eco-friendly BTS use direct ventilation, intelligent ventilation and heat exchange, for heat dissipation in the equipment rooms. Depending on the numbers of carriers, the eco-friendly BTS can consume as much as 2.0 kW [14].

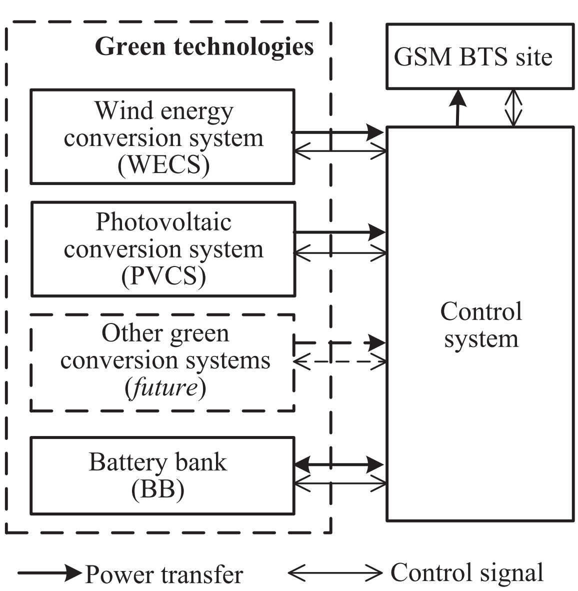

Fig. 1. Hybrid green energy system architecture for GSM BTS sites.

2.1. System models

At any time t, the hybrid green power generated in dc defined by Eq. (1) supplies the energy demand, and charges the battery bank (bb) provided the constraints imposed by the proposed control strategy is satisfied, else the generated power is dumped.

$$P_{gg}(t) = P_{wecs}(t) + P_{pvcs}(t). \tag{1}$$

P_{wecs} and P_{pvcs} are the power generated (in kW) at time t by the WECS and PVCS respectively.

The output power (in kW) of the WTG can only be computed accurately by using its own characteristic curve expressed as

$$P_{wt}(v) = \begin{cases} 0 & \text{for } v < v_{ci} \\ a_1v^3 + b_1v^2 + c_1v + d_1 & \text{for } v_{ci} \le v < v_1 \\ a_2v^3 + b_2v^2 + c_2v + d_2 & \text{for } v_1 \le v < v_2 \\ a_3v^3 + b_3v^2 + c_3v + d_3 & \text{for } v_2 \le v < v_{co} \\ 0 & \text{for } v \ge v_{co} \end{cases} \tag{2}$$

where v is the wind speed at hub height (m s^{-1}), v_{ci} is the cut-in wind speed (m s^{-1}), v_{co} is the cut-out wind speed (m s^{-1}), and a, b, c, and d are binomial coefficients. Eq. (2) is obtained by fitting the practical output characteristic curve using least squares method. A minimum of three binomial expressions were used in order to guarantee the fitting accuracy. Including the effect of altitude on air density [9], the proposed WECS model under real temperature and pressure becomes [12]

$$P_{wecs}(t) = z_f N_{wt} P_{wt}(v), \tag{3}$$

where z_f is the altitude factor at WTG hub height, N_{wt} is the total number of WTGs in the WECS.

The PVCS generated power (in kW) with respect to solar radiation is defined as:

$$P_{pvcs}(t) = N_{pv} A_{pv} p_f \eta_{mp,STC} I_T(t) \left(1 + \alpha_p \left(T_C(t) - T_{C,STC}\right)\right) \tag{4}$$

where N_{pv} is the number of PV modules in the PVCS, A_{pv} is the area of a single PV module (m^2), p_f is the packing factor, $\eta_{mp,STC}$ is the PV generator reference efficiency at standard test condition, I_T is the global solar radiation incident on the tilted PV (kWh m^{-2}), $T_{C,STC}$ is the cell temperature under standard test conditions (°C), α_p is the temperature coefficient of power (% °C^{-1}) and T_C is the cell temperature. The methods used in estimating T_C is available in Ref. [4].

The minimum state of charge of the battery bank is defined as:

$$SOC_{bb,min} = 1 - DOD_{bb,max}, \tag{5}$$

where, $DOD_{bb,max}$ is the maximum permissible depth of discharge of the battery bank. The energy retention capacity of the battery bank at time t is a function of the $SOC_{bb}(t)$, the self-discharge rate of the battery, σ (given as 0.14% day^{-1} [4]) and the size (the total nominal capacity) of the battery bank, S_{bb}, and is defined by Eq. (6), with the available power expressed as Eq. (7), where Δt is the simulation step time (considered as 1 h).

$$E_{bb}(t) = (1 - \sigma/24) \cdot S_{bb} \cdot SOC(t). \tag{6}$$

$$P_{bb,avail}(t) = \frac{E_{bb}(t)}{\Delta t} - SOC_{bb,min}. \tag{7}$$

The battery throughput and float life are two independent factors that limit the lifetime of batteries. The lifetime throughput of a battery, $E_{\mathrm{lt,tp}}$ (kWh) is the total amount of energy that can be cycled through the battery before replacement while the annual battery throughput, $E_{\mathrm{ann,tp}}$ (kWh yr^{-1}) is the amount of energy that cycle through the battery bank in one year. The battery bank life is determined by Ref. [15]

$$L_{\mathrm{bb}} = {}_{min}\left(\frac{N_{\mathrm{bb}}E_{\mathrm{lt,tp}}}{E_{\mathrm{ann,tp}}}, L_{\mathrm{bf}}\right) \tag{8}$$

where L_{bb} is the battery bank life (yr), N_{bb} is the number of batteries in the bank and $L_{\mathrm{b,f}}$ is the battery float life (yr). The proposed control strategy (discussed in Section 3) determines the optimal sizing/design configuration (S_h, i.e., $S_{\mathrm{wt}} = N_{\mathrm{wt}}$, $S_{\mathrm{pv}} = N_{\mathrm{pv}}A_{\mathrm{pv}}$ and $S_{\mathrm{bb}} = N_{\mathrm{bb}}E_{\mathrm{sb}}$, where E_{sb} is nominal capacity of a single battery) and the state of charge at any time t.

2.2. Economic considerations

The system's annualized cost ($C_{\mathrm{ann,sys}}$) is defined in terms of the present worth (PW) as [8]

$$C_{\mathrm{ann,sys}} = \frac{1}{L_{\mathrm{N}}}\sum_{h=1}^{h}\left(C_{h,\mathrm{ini}} + C_{h,\mathrm{rep(PW)}} + C_{h,\mathrm{om(PW)}} - C_{h,\mathrm{sal(PW)}}\right) \tag{9}$$

where, C_{ini} is the total initial cost (which includes both purchase and installation costs), $C_{\mathrm{rep(PW)}}$ is the total PW of replacement cost, $C_{\mathrm{OM(PW)}}$ is the total PW of annual operation and maintenance (OM) cost, $C_{\mathrm{sal(PW)}}$ is the PW of all salvage value, L_{N} is the life span of the project (yr) and h is the total number of the system's component unit with all cost expressed in US$.

If the lifetime L_h (yr) of component h is shorter than that of the project (i.e., $L_h < L_{\mathrm{N}}$), it might be necessary to purchase additional component h before the end of the project life span. Given that c_h (US$ unit^{-1}) and $c_{\mathrm{OM},h}$ (US$ unit^{-1} yr^{-1}) respectively are the present total cost and the annual operation and maintenance cost per unit sizing (design) parameter of component h, X_h ($=L_{\mathrm{N}}/L_h$ rounded to the greater integer) is the number of times component h is needed, and that salvage value of component h is assumed to decrease linearly from c_h to sv_h when component h operates along its lifetime L_h, the components of Eq. (9) is calculated as [8]:

$$C_{h,\mathrm{ini}} + C_{h,\mathrm{rep(PW)}} = c_h S_h \cdot \sum_{x=1}^{X_h} f_{(e,i)}^{x-1\cdot L_h}. \tag{10}$$

$$C_{h,\mathrm{OM(PW)}} = c_{\mathrm{OM},h} \cdot S_h \cdot \sum_{y=1}^{L_{\mathrm{N}}} f_{(e,i)}^{y} \tag{11}$$

$$C_{h,\mathrm{sal(PW)}} = S_h\left(sv_{h_{\mathrm{P}}} \cdot f_{(j,i)}^{L_{\mathrm{N}}} + sv_h \cdot \sum_{x=1}^{X_h-1} f_{(j,i)}^{x\cdot L_h}\right). \tag{12}$$

where S_h (unit) is the sizing (design) variable, $f_{(j,i)} = (1+r_j)/(1+r_i)$, $f_{(e,j)} = (1+r_e)/(1+r_j)$ and r_i, r_j and r_e are the annual interest, inflation and escalation rates (considered as 8%, 10% and 7%) respectively. The coefficient for salvage value of component h at present (i.e., at any time before the end of its life span) is determined by Ref. [8]

$$sv_{h_{\mathrm{P}}} = c_h - \left(\frac{c_h - sv_h}{L_h}\right) \cdot n_{\mathrm{y}}, \tag{13}$$

where n_{y} indicates the number of years of operation between the installation of the last component h and the end of the project life span. As observed, if the lifetime of the component is equal to or greater than the project lifetime (i.e., $L_h \geq L_{\mathrm{N}}$), $X_h = 1$, and no additional purchase of component h is required, that is, Eqs. (10) and (12) respectively reduces to

$$C_{h,\mathrm{ini}} + C_{h,\mathrm{rep(PW)}} = c_h S_h. \tag{14}$$

$$C_{h,\mathrm{sal(PW)}} = S_h sv_h \cdot f_{(j,i)}^{L_{\mathrm{N}}}. \tag{15}$$

The proposed system's cost of energy, COE (in US$ kWh^{-1}) is defined by

$$\begin{aligned} COE &= \frac{C_{\mathrm{ann,sys}}}{E_{\mathrm{ann,sys}}} \\ &= \psi\sum_{h=1}^{h} S_h \cdot \left(c_h \sum_{x=1}^{X_h} f_{(e,i)}^{(x-1)\cdot L_h} + c_{\mathrm{OM},h} \cdot \sum_{y=1}^{L_{\mathrm{N}}} f_{(e,i)}^{y} + sv_{\mathrm{ph}} \cdot f_{(j,i)}^{L_{\mathrm{N}}} \right. \\ &\qquad \left. + sv_h \cdot \sum_{x=1}^{X_h-1} f_{(j,i)}^{x\cdot L_h}\right) \end{aligned} \tag{16}$$

where $E_{\mathrm{ann,sys}}$ (kWh yr^{-1}) is the annual energy demand to be served by the system and ψ (kWh^{-1}) is the reciprocal of total energy demand to be served by the system during project life span, which is equal to $1/(L_{\mathrm{N}}E_{\mathrm{ann,sys}})$. Table 1 shows the economic specifications of components that constitute inputs of the proposed system design/techno-economic sizing procedure.

2.3. Problem formulation

The objective is to minimize the proposed system's cost of energy subject to reliable operation. Given that $S_{h,\mathrm{min}}$ and $S_{h,\mathrm{max}}$ are the minimum and maximum acceptable values of S_h respectively, c_p is the cost penalty per kWh unmet (deficit) energy demand, E_{d} is the total energy demand, and LPSP is the loss of power supply probability, the objective or fitness function is defined by

Table 1
Economic specification of components for proposed hybrid energy system sizing.

Characteristics	Wind turbine [16]	PV module [17]	Battery [18]	Inverter [19]
Model	Hummer H3.1-1 kW	SEDC 165 mono-crystalline	USB US-250	Sun shine solar VP100024 (1 kW)
Lifetime	15 yr	25 yr	Float life: 10 yr Lifetime throughput: 845 kWh	15 yr
Purchase cost per unit size	1250 US$ per WTG	280 US$ per module	205 US$ per battery	310 US$ per inverter
Installation cost per unit size	125 US$ per WTG	28 US$ per module	20.5 US$ per battery	31 US$ per inverter
Operation and maintenance cost, $c_{\mathrm{OM},h}$	12.5 US$ yr^{-1} per WTG	1 US$ yr^{-1} per module	1 US$ yr^{-1} per battery	1.5 US$ yr^{-1} per inverter
Salvage value, sv_h	30 US$ per WTG	10 US$ per module	0	0

$$_{min}COE(N_{\mathrm{wt}},N_{\mathrm{pv}},N_{\mathrm{bb}}) = \psi\sum_{h=1}^{h}S_h\cdot\left(c_h\sum_{x=1}^{X_h}f_{(e,i)}^{(x-1)\cdot L_h}+c_{\mathrm{OM},h}\cdot\sum_{y=1}^{L_N}f_{(e,i)}^{y}+s_{\mathrm{ph}}\cdot f_{(j,i)}^{L_N}+s_h\cdot\sum_{x=1}^{X_h-1}f_{(j,i)}^{x\cdot L_h}\right)+c_{\mathrm{p}}\cdot \mathrm{LPSP}\cdot E_{\mathrm{d}} \tag{17a}$$

subject to the constraints

$$\begin{aligned} &S_{h,\min}\le S_h\le S_{h,\max}\\ &\mathrm{SOC}_{\mathrm{bb,min}}\le \mathrm{SOC}_{\mathrm{bb}}(t)\le \mathrm{SOC}_{\mathrm{bb,max.}}\\ &\mathrm{LPSP}\le q\end{aligned} \tag{17b}$$

Although a zero value ($q = 0$) for the loss of power supply probability is desired for GSM BTS sites, q is set to vary within considerable reliability limits (considered here to be $\ge$95%) but with the inclusion of cost penalty for power supply shortages. In other words, at any time t when there is power supply shortage, the deficit energy supplied could be purchased. This will ensure proper compromise between reliability and cost for the optimal sizing of proposed system in typical applications.

The techno-economic viability of the proposed energy system is defined by Ref. [12]

$$K_{\mathrm{e}} = \frac{\eta_{\mathrm{rel}}}{\mathrm{COE}} \tag{18}$$

where, η_{rel} is the system's power supply reliability defined in terms of the LPSP (as $\eta_{\mathrm{rel}} = 1 - LPSP$). K_{e}, the key performance index (KPI) in kWh US^{-1}, of the system is an expression of the energy throughput of the system.

3. Control strategy

The focus of the control strategy is on the effective management of energy flow for improved stability and power supply reliability of the proposed system. It ensures the generation of proper power level between power sources, and the distribution for reliably satisfying the energy demand. The overall process control applied the genetic algorithm-based technique for optimal sizing of system's components and constrains the generation and distribution of power to reliably satisfy the energy demand while ensuring safe operation of the system. Fig. 2 shows the control design of the proposed hybrid green energy system. This study assumed that the peak power trackers (PPTs) and the proposed control algorithm are ideal (lossless).

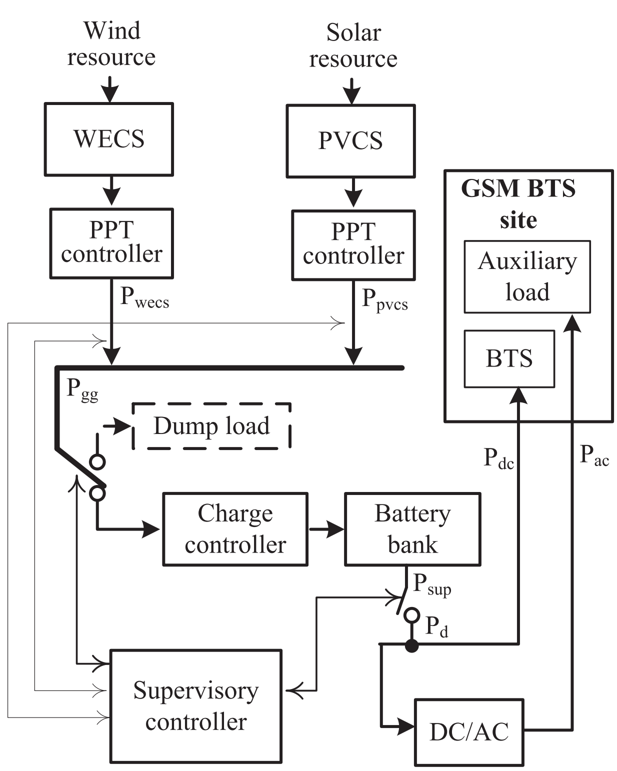

Fig. 2. Control design of proposed hybrid green energy system.

The PPTs will keep the PV array and WTGs operating at their maximum power operating points while the supervisory controller regulates the system for reliable operation. The system is designed to operate while the battery bank is either in the passive (idle) or active (charging/discharging) modes of operation provided the constraints imposed by the energy management system are satisfied. The battery bank is said to be in the passive mode when $\Delta E(t) = 0$, i.e., when the total power generation at time t is equal to the total load consumed at t. Under this condition, $\mathrm{SOC}_{\mathrm{bb}}(t) = \mathrm{SOC}_{\mathrm{bb}}(t-1)$. In the active mode, when $\mathrm{SOC}_{\mathrm{bb}}(t) > \mathrm{SOC}_{\mathrm{bb,max}}$, the control disconnects the battery from charging while switching on the dump load and dump excess energy based on imposed technical constraint (see Fig. 3). Conversely, when $\mathrm{SOC}_{\mathrm{bb}}(t) = \mathrm{SOC}_{\mathrm{bb,min}}$, the control disconnects the supplied load from the battery bank.

At any time t, the state of charge of the battery bank $\mathrm{SOC}_{\mathrm{bb}}(t)$ is defined by:

$$\mathrm{SOC}_{\mathrm{bb}}(t) = \mathrm{SOC}_{\mathrm{bb}}(t-1)+\left(P_{\mathrm{gg}}(t)\cdot\eta_{\mathrm{b}}\cdot\Delta t-P_{\mathrm{d}}(t)\cdot\Delta t\right)/S_{\mathrm{bb}} \tag{19a}$$

$$\begin{aligned}\mathrm{SOC}_{\mathrm{bb}}(t) &= \mathrm{SOC}_{\mathrm{bb}}(t-1)+\left(E_{\mathrm{gg}}(t)\cdot\eta_{\mathrm{b}}-E_{\mathrm{d}}(t)\right)/S_{\mathrm{bb}}\\ &= \mathrm{SOC}_{\mathrm{bb}}(t-1)+\Delta E(t)/S_{\mathrm{bb}}\end{aligned} \tag{19b}$$

where S_{bb} (kWh) is the total nominal storage capacity of the battery bank, η_{b} is the battery charge/discharge efficiency and other parameters previously defined. The net energy difference at any time, $\Delta E(t)$, determines the charge/discharge provided the constraints imposed by the proposed control strategy are satisfied.

To account for hourly and seasonal variations in energy consumption, the power demand at any time, t, is [12]

$$\begin{aligned}P_{\mathrm{d}}(t) &= (P_{\mathrm{dc}}(t)+P_{\mathrm{ac}}(t)/\eta_{\mathrm{inv}})\times(1+\delta_{\mathrm{h}}\delta_{\mathrm{d}})\\ &= P_{\mathrm{L}}(t)\times(1+\delta_{\mathrm{h}}\delta_{\mathrm{d}})\end{aligned} \tag{20}$$

where, P_{dc} (kW) is the dc power consumed by the BTS, P_{ac} (kW) is the ac power consumed by the auxiliary equipment, P_{L} (kW) is the typical power consumed by the BTS site, η_{inv} is the inversion efficiency, and δ_{h} and δ_{d} are the hourly and the daily noise input values, respectively, drawn from normal distribution with an average of zero and standard deviation equal to the noise factor.

Fig. 3 shows the control model for the proposed hybrid green energy system. The constraints imposed on the system are as follows.

- If $[\mathrm{SOC}_{\mathrm{bb,min}} < \mathrm{SOC}_{\mathrm{bb}}(t) || \mathrm{SOC}_{\mathrm{bb}}(t) \le \mathrm{SOC}_{\mathrm{bb,max}}]$ Then

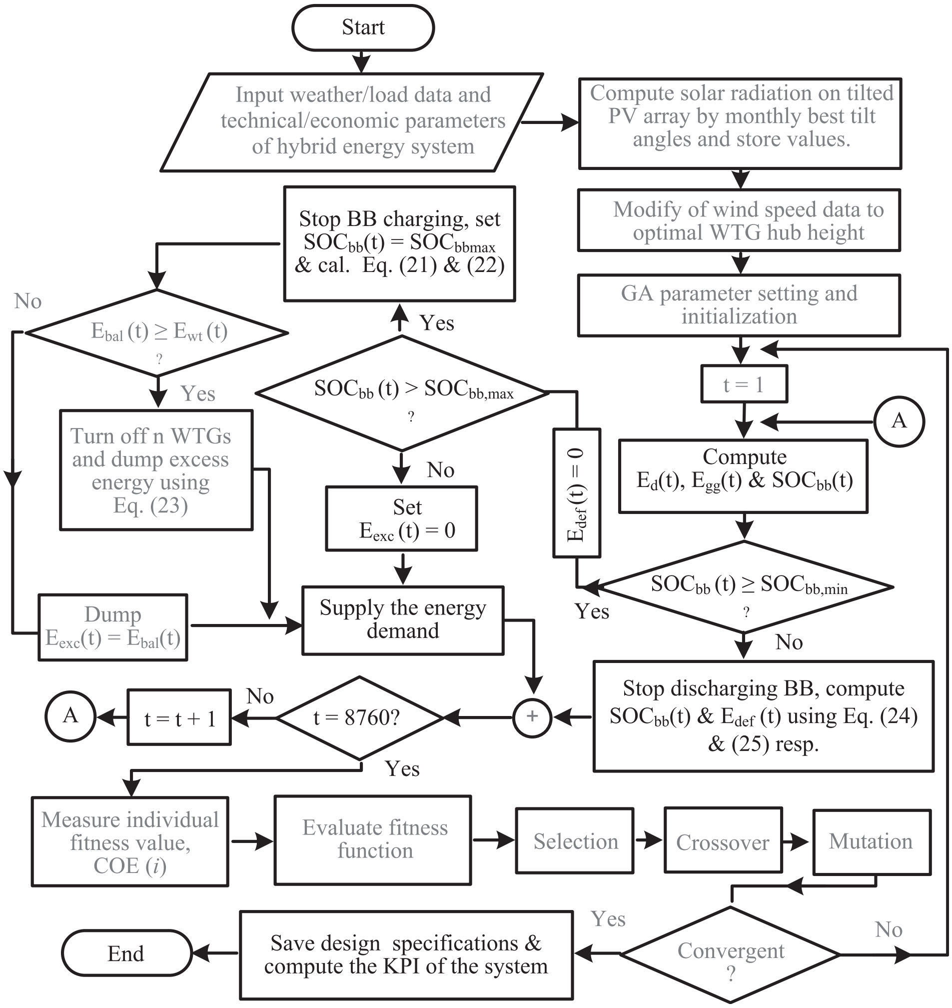

Fig. 3. Control model for the proposed hybrid green energy system.

Supply the energy demanded with the battery bank working in any of the three modes of operation depending on the magnitude of $\Delta E(t)$. Set dump and excess energy supply to zero.

- ElseIf [$SOC_{bb,min} \leq SOC_{bb}(t) || SOC_{bb}(t) > SOC_{bb,max}$] Then

Supply the energy demanded and disconnects the battery bank from source, with the battery bank working in the discharging mode of operation and set $SOC_{bb}(t) = SOC_{bb,max}$. Calculate the energy balance, and energy generation from a WTG using Eq. (21) and Eq. (22) respectively. Afterward check

$$E_{bal}(t) = \Delta E(t) - S_{bb}\left(SOC_{bb,max} - SOC_{bb}(t-1)\right) \tag{21}$$

$$E_{wt}(t) = \frac{P_{wecs}(t) \cdot \Delta t}{N_{wt}} \tag{22}$$

If [$E_{bal}(t) \geq E_{wt}(t)$] Then turn off n WTGs at time t where n is the integer value of $E_{bal}(t)/E_{wt}(t)$ for which $0 \leq n \leq N_{wt}$. Compute the excess energy supply (in kWh) using Eq. (23). Else set the excess energy supply to $E_{bal}(t)$. Switch on the dump load and dump excess energy.

$$E_{exc}(t) = E_{bal}(t) - nE_{wt}(t) \tag{23}$$

- Else

Disconnect the supply load and compute $SOC_{bb}(t)$ [using Eq. (24)] and the deficit in energy supplied [using Eq. (25)]

Table 2
Calibration results of proposed WTG model [Eq. (3)] using data supplied by Ref. [16].

Parameters ($m\ s^{-1}$)	i	a_i	b_i	c_i	d_i
$v_{ci} = 3$, $v_1 = 9$	1	−0.000333	0.0216	−0.0596	0.03433
$v_2 = 13$	2	0.0025	−0.0925	1.15	−3.68
$v_{co} = 22$	3	−0.0001361	0.007065	−0.1117	1.689

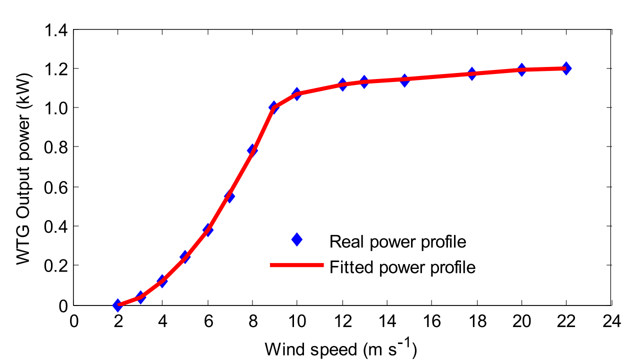

Fig. 4. Comparison of output characteristics between the proposed WTG models and that supplied by the manufacturer.

Table 3
Optimal sizing configuration of proposed hybrid energy system for studied locations.

Studied locations	N_{pv}	N_{wt}	N_{bb}
Abuja	40	3	48
Benin City	57	3	52
Sokoto	19	2	20

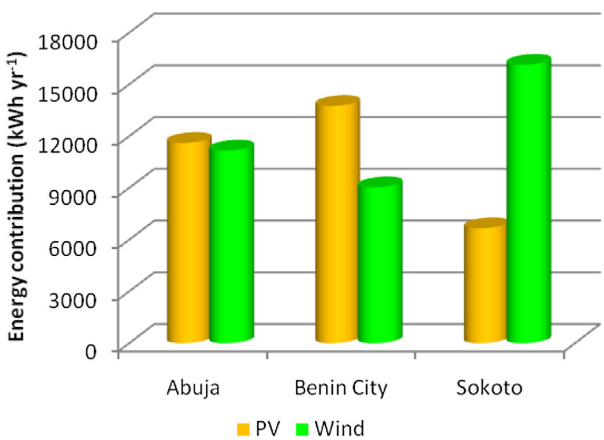

Fig. 5. Comparison of annual energy contribution by part for study locations.

$$\mathrm{SOC}_{bb}(t) = \mathrm{SOC}_{bb}(t-1) + E_{gg}(t) \cdot \eta_b / S_{bb} \tag{24}$$

$$E_{def}(t) = E_d(t) \tag{25}$$

The genetic algorithm (GA) uses three operators (selection, crossover and mutation) for the optimal sizing of the proposed system. The selection process begins with the evaluation of the initial system design configuration or chromosome (either chosen or set by default) to determine if they provide reliable power supply (determined in terms of LPSP in this study) to the load otherwise new chromosome is determined. If the evaluation qualified chromosome has a lower COE than the lowest COE value obtained at the previous iterations, this system configuration (chromosome) is considered to be the optimal solution for the minimization problem in this iteration. This optimal solution will be replaced by better solutions, if any, produced in subsequent GA generations during the program evolution. After the selection process, the optimal solution will then be subject to the crossover and mutation operations in order to produce the next generation population until a criterion that determines the convergence is satisfied or when a pre-specified number of generations have been reached.

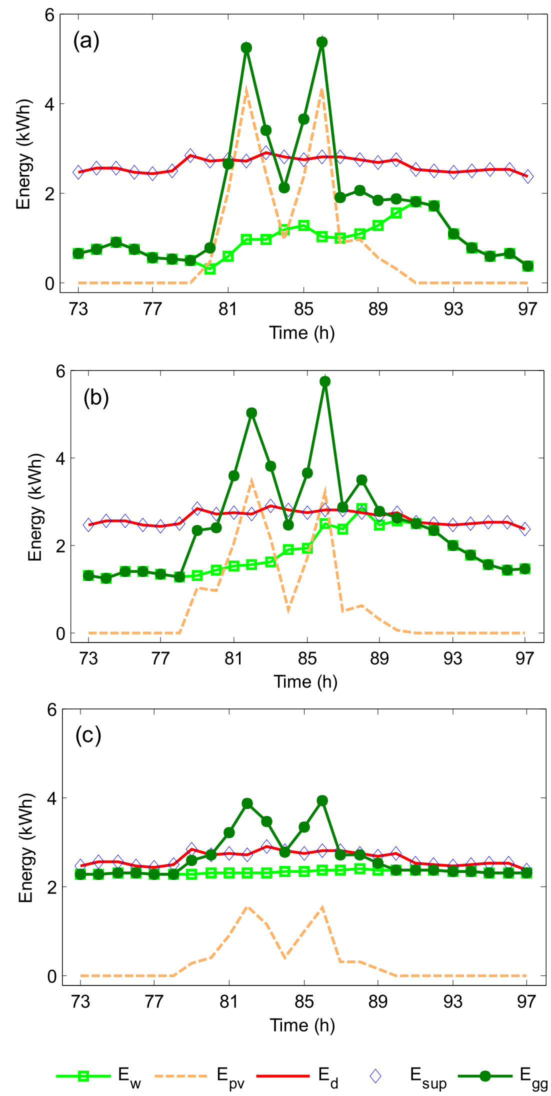

Fig. 7. Electrical characteristics of proposed energy system for a typical day: January 4 (a) Abuja, (b) Benin City, and (c) Sokoto respectively.

4. Simulation

The overall process simulation of the proposed design utilized the load profile of a typical green GSM BTS site considered for Abuja, Benin City and Sokoto. Abuja is located on latitude 9.08 °N

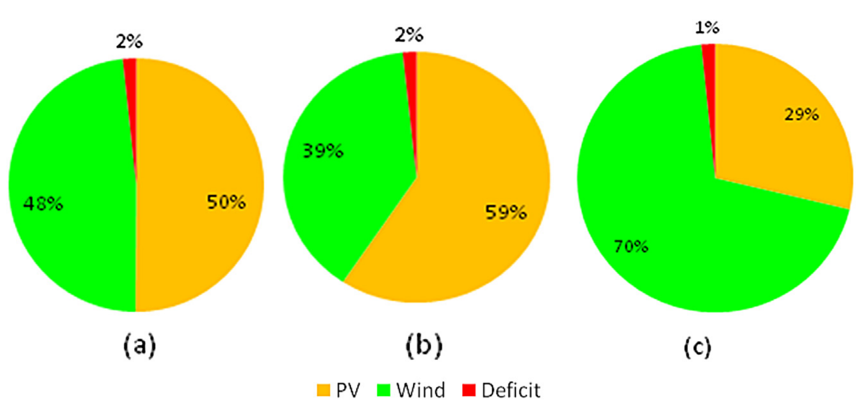

Fig. 6. Comparison of annual energy contribution by part in percentage for study locations.

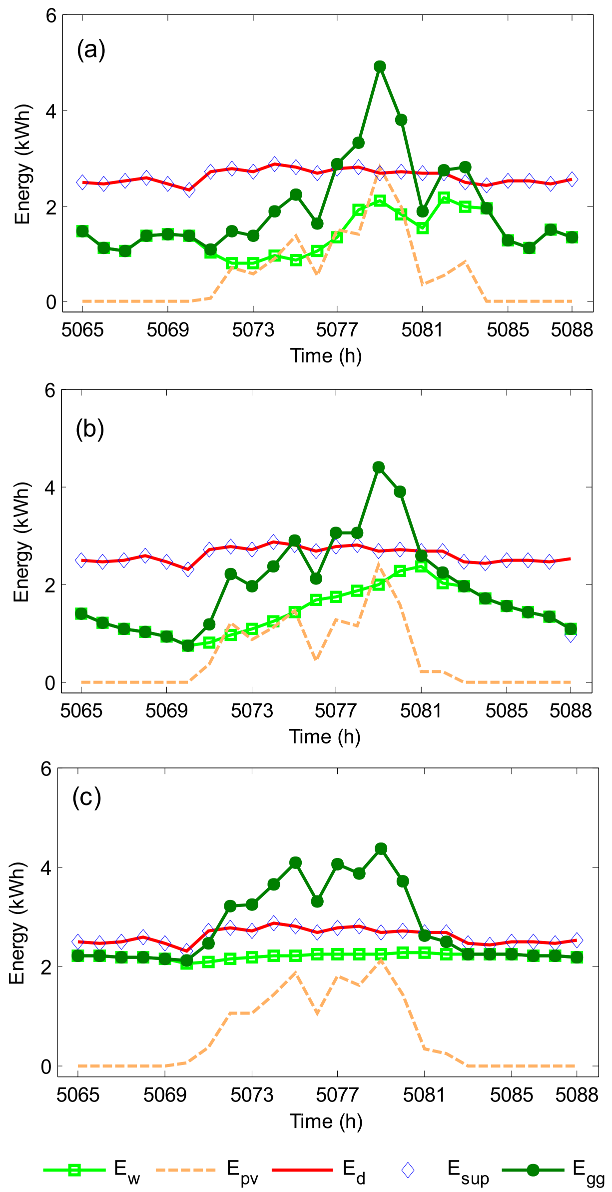

Fig. 8. Electrical characteristics of proposed energy system for a typical day: July 31 (a) Abuja, (b) Benin City, and (c) Sokoto respectively.

and longitude 7.53 °E, Benin City on latitude 6.34 °N and longitude 5.63 °E, and Sokoto on latitude 13.06 °N and longitude 5.25 °E respectively in the central, southern and northern regions of Nigeria. A comprehensive description of the meteorological conditions of these locations is available in Ref. [9]. This study applied hourly data on solar radiations, wind speed and GSM BTS load discussed in previous studies [11,12] for simulation of proposed hybrid green energy system.

The calibration and validation of the proposed WECS model used data supplied for Hummer H3.1-1 kW WTG by the manufacturer [16]. The installation (hub) height of the wind turbine has a great influence on the available wind energy as wind speed increases with increasing height. Therefore, based on the weather data measured at the study site, the optimal height for harnessing wind energy is determined. The method for computing the monthly optimal tilt angles of solar collectors oriented due south for studied locations is available in Ref. [20]. The design configuration for a loss of power supply to GSM BTS sites below 2% (LPSP $\leq$ 0.02) intended for this study is presented, discussed and compared with traditional approaches in following section. For simplicity, it is assumed that the cost implication for not supplying a kW load demand at any time *t* (i.e., cost implication per unit unmet energy demand) is equal to the COE per kWh for diesel-generator system. The project life span is assumed to be the same as that of the PV module which has a longer lifetime of 25 years. To limit the scope of this study, HOMER (Hybrid Optimization Model for Energy Renewables) computer model is applied to design the diesel generator system utilized for comparison study. The capital and maintenance costs of the diesel generator respectively are 600 US\$ kW^{-1} and 0.1 US\$ kW^{-1} h^{-1} with a service life of 15,000 h [21,22]. The fuel price varies from one location to another (considered here as 1.0–1.1 US\$ L^{-1}) owing to additional cost of transportation of the fuel which varies from one part of the country to another. However, the environmental cost implication of the diesel power generated is neglected in COE analysis as it is beyond the scope of present study.

5. Results and discussions

Table 2 shows the calibration results of the proposed WTG model of Eq. (3) while Fig. 4 shows the validation results. The

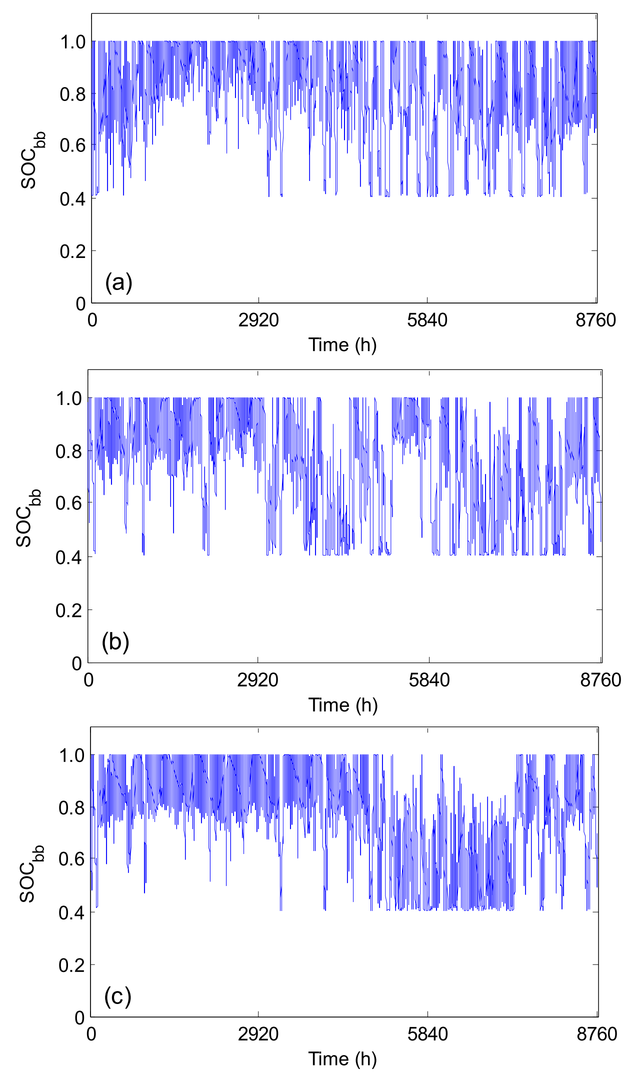

Fig. 9. SOC of battery bank of proposed system for a simulation period of 1 year (a) Abuja, (b) Benin City, and (c) Sokoto respectively.

validation results indicate that there is an excellent agreement between the proposed power profile and that supplied by the manufacturer.

Tables 3 shows the optimum sizing specification for the proposed hybrid PV-Wind energy system for LPSP $\leq$ 0.02, under the same load demand profile (for a simulation period of 1 year) for the studied locations in Nigeria. The specifications selected are as follows. SEDC 165 module of $P_{max} = 165$ W$_p$, $A_{pv} = 1.29$ m^2, $V_{dc} = 24$ V, $T_{C,STC} = 25$ °C, and $\alpha_p = -0.48\%$ °C^{-1}. Hummer (H3.1) of DC current and $P_r = 1$ kW, $P_{max} = 1.2$ kW, $v_{ci} = 3$ m s^{-1}, $v_{co} = 25$ m s^{-1}. USB US-250 battery with $E_{sb} = 1.35$ kWh (i.e., 225 Ah at a nominal battery voltage of 6 V).

A study of the results presented in Table 3 shows that the variation of the optimal sizes of the hybrid energy system components from one part of the country to the other, indicating the dependance of renewable sources on climatic conditions. This justifies the need for the determination of the optimal design specification of the renewable energy sources for any given location as no two locations could perform optimally under same design specification.

Figs. 5 and 6 show a comparison of the energy contribution by part. As observed, wind energy potential decreases from the northern (Sokoto) to the southern (Benin City) part of Nigeria. The larger percentage of solar energy contribution for Abuja and Benin City indicates the viability of the solar energy potential these regions in Nigeria.

In order to effectively study the operational and control performance of the proposed system, two typical days (January 4 and July 31) randomly chosen within the simulation period have been considered as shown in Figs. 7 and 8.

During the early and late hours of the day when solar energy is unavailable the system's energy generation is considerably low. During these periods, the energy storage provides the deficit energy needed to balance the energy demand requirement. At about noon, i.e., between 7 and 17:00 h of the day when solar energy is available the system's energy generation is considerably high throughout the studied locations, irrespective of the availability of wind power. This demonstrates the viability of solar energy potential across the country. The surplus energy is stored to be used in periods of short supply. These results validate the reliable operational performance of the proposed system. Fig. 9 shows the state of charge of the battery bank of the proposed hybrid wind-photovoltaic system. As observed, the proposed energy management strategy constrains the SOC of the battery at any time to fall within the defined minimum and maximum acceptable limits of 40% and 100%. This will ensure a longer lifetime for the battery banks.

Fig. 10 shows a comparison of proposed hybrid green energy system and conventional (diesel-only and diesel-battery backup) generator systems. The variation in the COE produced by the conventional generating systems results from the cost variation per liter of diesel consumed owing to additional cost of transportation which varies from one part of the country to another. In terms of techno-economy, the implementation of proposed system guarantees over 70% reduction in the COE across studied locations compared to conventional systems, but at a reliability cost (system downtime) of about 2%. Nevertheless, the optimum COE for the

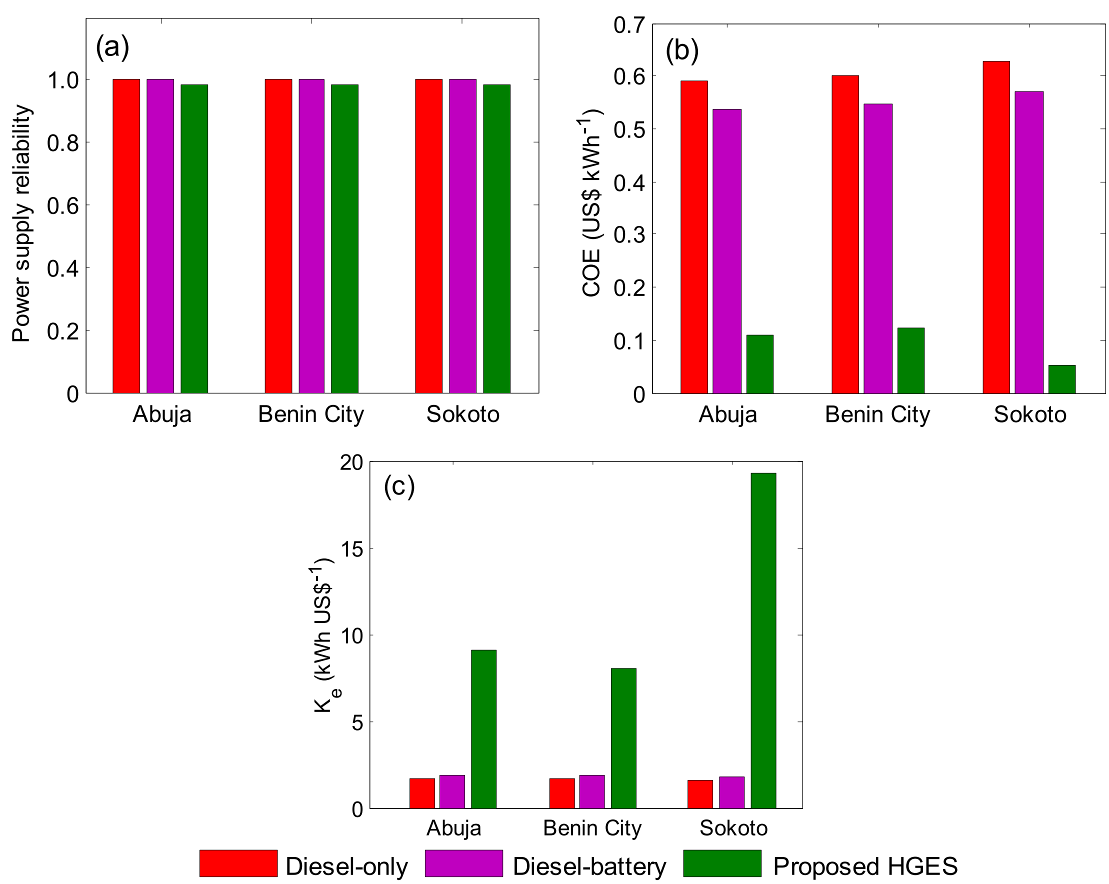

Fig. 10. Performance comparison of proposed hybrid green energy system and conventional (diesel-only and diesel-battery backup) systems.

Table 4
Comparison of proposed system techno-economic viability for various reliability limit.

Studied locations	LPSP	η_{rel}	COE (US\$ kWh^{-1})	K_e (kWh US\$$^{-1}$)
Abuja	0.0411	0.9589	0.1052	9.12
	0.0364	0.9636	0.0999	9.65
	0.0296	0.9704	0.1054	9.20
	0.0171	0.9829	0.1079	9.11
	0.0082	0.9918	0.1081	9.17
	0.0000	1.0000	0.1119	8.94
Benin City	0.0454	0.9546	0.1158	8.24
	0.0369	0.9631	0.1158	8.32
	0.0282	0.9718	0.1231	7.89
	0.0168	0.9832	0.1227	8.01
	0.0075	0.9925	0.1240	8.00
	0.0000	1.0000	0.1270	7.87
Sokoto	0.0487	0.9513	0.0438	21.74
	0.0392	0.9608	0.0443	21.68
	0.0259	0.9741	0.0498	19.58
	0.0161	0.9839	0.0511	19.26
	0.0065	0.9935	0.0538	18.46
	0.0000	1.0000	0.0626	15.97

proposed energy system accounts for the opportunity costs for the loss of power supplied to the GSM BTS sites.

As noticed, the overall energy throughput of the proposed system varies from about 8.01 kWh US\$$^{-1}$ in Benin City to 19.26 kWh US\$$^{-1}$ in Sokoto and this compares more favorably to the conventional system (about 2 kWh US\$$^{-1}$). The COE produced by the utility grid where available in the country is about 0.1519 US\$ kWh^{-1}. Although the cost appears to be in close range with that of the proposed system in Abuja and Benin City, the new parameter (K_e) proposed in this study to determine the techno-economic viability indicates that the proposed system produced more than twice as high the energy produced by the utility grid per US\$ in Abuja and Benin City (i.e., about 9.11 and 8.01 kWh US\$$^{-1}$ respectively, compared to the grid energy throughput of about 3.29 kWh US\$$^{-1}$). This is because the reliability of grid supplied electricity in the country is about 50% [11]. The higher the energy throughput of an energy system the better the system is (in terms of reduced cost and increased reliability).

To further demonstrate the techno-economic viability of the green energy technology and the significance of the KPI proposed for the evaluation of energy generation system we performed sensitivity analysis by varying the loss of power supply probability for proposed hybrid energy system. Table 4 shows the comparison of proposed system techno-economy for the loss of power supply not exceeding 5%.

As observed, the optimal economic costs tend to increase with the power supply reliability of the energy system. Given a desired tolerance of 5% unavailability for a typical application, the highest K_e-values indicates the best compromise between cost and reliability. Based on the K_e-values, a system designed with a downtime (LPSP) of about 4% (in Abuja and Benin City) and downtime of about 5% (in Sokoto) gives the overall best improvement of system energy throughput of about 0.71, 0.45, 5.77 kWh, per US\$ investment respectively, compared to systems designed never to go down.

6. Conclusion

This study has developed the optimum control model for a hybrid wind-photovoltaic energy system for the cost effective and reliable energy solution to GSM BTS sites. In addition, the study introduced the concept of the energy throughput of a system as a key performance indicator (KPI) for determining the overall performance characteristic of an energy system. The proposed KPI is an expression of the techno-economic viability of an energy system measured in terms of per unit cost of energy supplied. The improvement of an average energy throughput of over 12 kWh US\$$^{-1}$ as compared to the utility grid with about 3.29 kWh US\$$^{-1}$, or the diesel generator with about 2 kWh US\$$^{-1}$ (see Fig. 9) shows the excellent performance of the proposed over the existing systems, yet with a considerably excess energy capacity generation (about 6–17% of energy demand) that could improve the lives of the host community. If the legislation and enabling conditions for electricity sellback to the national grid are put in perspective, the gains would also encourage extensive utilization of renewable resources in other sectors of the economy and thereby making the environment much more friendly and safe.

References

[1] R.S. Kovats, D. Campbell-Lendrum, F. Matthies, Risk Anal. 25 (6) (2005) 1409–1418.
[2] J.R. VandeWeghe, C. Kennedy, J. Ind. Ecol. 11 (2) (2007) 133–144.
[3] A.S. Adegoke, I.T. Babalola, Am. J. Sci. Ind. Res. 2 (5) (2011) 707–712.
[4] S. Diaf, D. Diaf, M. Belhamel, M. Haddadi, A. Louche, Int. J. Energy Policy 35 (2007) 5708–5718.
[5] E. Vine, Energy Effic. 1 (2009) 49–63.
[6] O. Ekren, B.Y. Ekren, Appl. Energy 87 (2010) 592–598.
[7] S.O. Oyedepo, Renew. Sustain Energy Rev. 16 (2012) 2583–2598.
[8] A.A. Nafeh, Int. J. Green Energy 8 (1) (2011) 25–43.
[9] M.S. Okundamiya, A.N. Nzeako, Int. J. Green Energy 10 (2) (2013) 205–218.
[10] Z. Hasan, H. Boostanimehr, V.K. Bhargava, IEEE Commun. Surv. Tut. 13 (4) (2011) 524–540.
[11] M.S. Okundamiya, J.O. Emagbetere, E.A. Ogujor, Sci. World J. 2014 (2014) article ID 947281, 13 pages, http://dx.doi.org/10.1155/2013/947281.
[12] M.S. Okundamiya, Modeling and Optimization of Hybrid Energy System for GSM BTS Sites in Developing Coutries, unpublished PhD thesis, University of Benin, Benin City, Nigeria, 2014.
[13] Huawei Technologies, Save Energy and Reduce Emissions to Achieve Sustainable Development and Improve Corporate Competitiveness, 2012 Huawei Whitepaper for Saving Energy and Reducing Emissions, 2012, pp. 1–20. China.
[14] Z. Jianguo, Z. Qiang, G. Yu, P. Yingwen, China Mobile in Action, Huawei Communicate, December, 2008, pp. 31–35.
[15] National Renewable Energy Laboratory (NREL), Hybrid Optimization Model for Electric Renewable (HOMER) Software, 2010.
[16] Hummer, Hummer H 3.1-1 kW Specification Sheet, 2013. Available from: http://www.allwindturbine.com/products_info/H3-1-1KW-Off-Grid-Wind-Turbine-229357.html (accessed 18.04.13).
[17] Solar Energy DC: Technical Data Sheet and Price lists, Available on: www.energiesolairedc.com, http://www.solarenergydc.com/index.php/en/component/virtuemart/standard-solar-panel-kits/165w-solar-panel-kit-22-detail?Itemid=0 (accessed 21.12.13).
[18] S.K. Nandi, H.R. Ghosh, Energy 35 (2010) 3040–3047.
[19] Sunshine Power Inverter Technical Specifications and Price List, http://www.sunshinesolar.co.uk/khxc/gbu0-prodshow/VP100024.html.
[20] M.S. Okundamiya, A.N. Nzeako, Res. J. Appl. Sci. Eng. Technol. 3 (12) (2011) 1386–1392.
[21] S.L. Trazouei, F.L. Tarazouei, M. Ghiamy, Int. J. Renew. Energy Res. 3 (2) (2013) 403–411.
[22] Z. Girma, Int. J. Renew. Energy Res. 3 (3) (2013) 735–744.